Energy Efficiency of MIMO Transmission Strategies in Wireless Sensor Networks

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Abstract

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Keywords: Cooperative MIMO, Energy Efficiency, MIMO Transmission, Mobile Agent, Sensor Network, Spectral Efficiency, Virtual MIMO, Wideband Regime.

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I. INTRODUCTION

Wireless sensor networks are distinct from conventional wireless networks with dense sensor deployment and stringent power constraint [1]. Therefore, cooperation among groups of sensors in close proximity is a necessity to realize the great potential of wireless sensor networks in typically harsh communication environments. On the other hand, by allowing sensor nodes to cooperate on communication to form multi-input multi-output (MIMO) systems, recent progress in wireless MIMO communications can be exploited to boost the system throughput, or equivalently reduce the energy consumption for the same throughput and bit error rate (BER) target, which is crucial for sensor applications.

Due to the physical size and power limitations, most sensor nodes are typically equipped with one antenna. Recently people have considered a novel view on sensor networks where various subsets of sensors form non-linear arrays for communication purposes, to take advantage of the advanced space-time coding and processing techniques. However, when analyzing the energy efficiency of MIMO transmission strategies in sensor networks, two additional factors should be given special considerations: the circuit energy consumption and the cooperation penalty. The circuit power utilization of a cooperative MIMO system increases linearly with the number of cooperative nodes, which is significant for short-range applications such as sensor networks. Furthermore, as the elements of the virtual antenna array are not wired together, cooperative nodes must communicate among themselves to share and coordinate information for MIMO transmission.

Energy analysis on cooperative MIMO was investigated in [2] recently, where it is shown that the Alamouti space-time block coding (STBC) scheme on a cooperative 2×2 MIMO is more energy efficient than the traditional single-input single-output (SISO) approach when the transmission distance is larger than a small threshold (around 30 m). Our paper assumes the following differences. First, we introduce powerful mobile agents (MA) at the receive side as advocated in [11], which are assumed to be equipped with antenna arrays and complex processors and transceivers. Therefore, while sophisticated detection techniques can be safely employed at the receiver, its energy consumption can be excluded from the budget of the overall sensor network, which allows us to focus on the energy analysis at the cooperative transmit end. Secondly, besides STBC schemes [10], another important type of MIMO techniques, spatial multiplexing (SM, also known as BLAST) [3], is also analyzed in details, both for the wideband asymptotes and for more realistic systems. Finally, in the analysis of practical systems, SM schemes are investigated with both optimal and sub-optimal detection, and with both fixed and adaptive signaling. Analytical results are given whenever applicable.

This paper is organized as follows. Section II presents the system model and our assumptions on analysis. The transmit energy efficiency of relevant SISO, SIMO and MIMO systems is studied for wideband asymptotes and more realistic systems in Section III and IV, respectively. The analysis of this part does not consider the circuit energy consumption and cooperation penalty, which are explicitly addressed in Section V. Numerical results are given in Section VI. Finally, Section VII contains some concluding remarks.

II. SYSTEM MODEL

We assume a hierarchical network structure, in which most plain sensor nodes are stringently limited in processing capability and power, while a few powerful mobile agents take over the burden of complicated network operation and signal processing. These mobile agents, furnished with superior communication and processing units, can traverse the network to collect data, and reach back to remote control centers through high-speed connections. Examples of mobile agents include manned/unmanned airplanes or vehicles, or specially designed light nodes that can hop around in the network. This architecture assumes certain advantages in energy efficiency over the traditional flat multi-hop ad hoc network [11]. In this paper, we further investigate the possible advantages of cooperative MIMO transmission in wireless sensor networks with mobile agents (SENMA), which can be similarly coined as M-SENMA.

We assume that at some moment N_T neighboring nodes in a SENMA intend to cooperate in transmission to a MA equipped with N_R antennas. Independent frequency nonselective Rayleigh fading is assumed for the channels between each node and the MA, on top of the common path loss[1]. The equivalent discrete-time MIMO system can be described as

$$\mathbf{Y} = \mathbf{HX} + \mathbf{N} , \tag{1}$$

where **Y** is the received signal at the MA; **X** contains the substreams transmitted by the cooperative nodes; **H** is an $N_R \times N_T$ channel matrix that captures the channel characteristics between transmit and receive antenna arrays, whose entries are modeled as independent and identically distributed (i.i.d.) normalized complex Gaussian random variables; and **N** is the background noise, assumed to be circularly symmetric Gaussian with variance N_0 for each component. The common path loss is incorporated in the power of **X**. Throughput the paper, it is assumed that the channel is quasi-static and is known at the receiver but not at the transmitter. Finally, we assume a slotted time division duplexing system, and the existence of a reverse signaling channel from the MA to the cooperative sensor group as in [11].

Two types of MIMO technologies, STBC and SM, are considered in this paper, both easily implemented at the transmission end and thus suitable for sensor applications [6]. The STBC scheme sends out an $N_T \times B$ space-time block **X** with orthogonal rows per channel use to realize full diversity gain. The maximum likelihood (ML) detection of each transmitted symbol is decoupled, equivalently represented as

$$y = \| \mathbf{H} \|_F \; x + n , \tag{2}$$

where $\| \mathbf{H} \|_F^2$, the Frobenius norm of **H**, is Gamma distributed with parameters $N_T N_R$ and 1, and the equivalent noise n still has variance N_0. It can be shown that the spectral efficiency (bits/s/Hz) of the STBC system is given by

$$C(\mathrm{SNR}) = rE\left[\log\left(1 + \| \mathbf{H} \|_F^2 \ \mathrm{SNR} / N_T \right) \right], \tag{3}$$

where $r = N_T / B$ is the rate of STBC, and SNR denotes the identical energy per user per block symbol divided by N_0. This expression should be compared to that of a SIMO system with maximum ratio combining (or a SISO system):

$$C(\mathrm{SNR}) = E\left[\log\left(1 + |A|^2 \ \mathrm{SNR} \right) \right] \tag{4}$$

where $|A|^2$ is Gamma distributed with parameters N_R and 1 (or exponentially distributed with unit mean).

While STBC emphasizes maximizing the diversity gain, the SM scheme mainly focuses on maximizing the spatial multiplexing gain and is especially suitable for high-rate communications [14]. In SM each transmit antenna sends an independent symbol each time, which can be viewed as a space-only code without loss of generality:

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} , \tag{5}$$

where **y**, **x** and **n** denote column vectors. The spectral efficiency of SM is given by

$$C(\mathrm{SNR}) = E\left[\log\left| I + \mathbf{H}^H \mathbf{H} \cdot \mathrm{SNR} \right| \right], \tag{6}$$

where SNR is defined on the per-user basis as before.

III. Energy Analysis in the Wideband Regime

We first analyze several relevant transmission strategies in the wideband regime, corresponding to high-to-optimal energy efficiency. The approach is to approximate the spectral efficiency as an affine function of energy per bit normalized to the noise spectral density (i.e., E_b / N_0) in the zero SNR neighborhood as

$$C\left(E_b / N_0 \right) = \frac{S_0}{10\log_{10} 2} \left(10\log_{10}\left(E_b / N_0 \right) - 10\log_{10}\left(E_b / N_0 \right)_{\min} \right), \tag{7}$$

where the two key parameters $(E_b / N_0)_{\min}$, the minimum required energy for reliable communications, and S_0, the wideband slope of spectral efficiency-energy efficiency curve in terms of bits/s/Hz/3 dB, can be obtained as [13]

$$\frac{E_b}{N_0}_{\min} = \beta \frac{\ln 2}{\dot{C}(0)}, \quad S_0 = \frac{2\left[\dot{C}(0) \right]^2}{-\ddot{C}(0)}, \tag{8}$$

with $\dot{C}$, $\ddot{C}$ the first and second derivatives of the spectral efficiency (3), (4), and (6) at SNR = 0, and β the parameter relating E_b / N_0, SNR, and $C(\mathrm{SNR})$ as

$$\frac{E_b}{N_0} = \beta \frac{\mathrm{SNR}}{C(\mathrm{SNR})}, \tag{9}$$

which equals to 1 for SISO and SIMO, r for STBC, and N_T for SM. These two parameters for SISO, SIMO, STBC and SM systems with Raleigh fading are presented in Table I.

TABLE I Wideband Analysis of Communications Systems Subject to Rayleigh Fading

	SISO	SIMO	STBC	SM
$(E_b / N_0)_{\min}$	$\ln 2$	$\ln 2 / N_R$	$\ln 2 / N_R$	$\ln 2 / N_R$
S_0	1	$\frac{2N_R}{N_R + 1}$	$\frac{2rN_T N_R}{N_T N_R + 1}$	$\frac{2N_T N_R}{N_T + N_R}$

Wideband analysis shows that receive diversity effectively lowers the minimum required energy by a factor of N_R. However, $(E_b / N_0)_{\min}$ alone does not reveal the whole picture as it could not differentiate various communication systems with receive antenna arrays but different transmission strategies. On the other hand, S_0 demonstrates their differences in spectral efficiency given certain energy efficiency in the wideband regime. In general, we have

$$1 \le \frac{2N_R}{N_R + 1} \le \frac{2N_T N_R}{N_T N_R + 1} \le \frac{2N_T N_R}{N_T + N_R}. \tag{10}$$

[1] Rayleigh fading is commonly assumed in MIMO and SENMA studies whenever rich scattering exists in environments. This can be justified when sensor nodes are distributed in a building or forest. In applications with line-of-sight communications, Ricean model can be exploited.

But as the number of antennas grows, the S_0 of SIMO and STBC approaches a limit of 2, while that of SM grows without bound. We know that the wideband slope for the AWGN SISO channel is 2, which is reduced to 1 here due to Raleigh fading. Essentially, the diversity in SIMO and STBC alleviates the fading effect and brings it back to 2. The transmit diversity of STBC facilitates this process, whose effect quickly diminishes when there are sufficient receive antennas. Furthermore, full-rate ($r=1$) orthogonal complex designs for STBC only exists for $N_T=2$, further counteracting possible advantages of STBC over SIMO. On the other hand, with sufficiently large N_T, the S_0 of SM approaches $2N_R$, resulting a tremendous boost of spectral efficiency even in the low-power regime. Actually just having as many transmit antennas as receive ones leads to $S_0=N_R$, already half of the ultimate limit. These observations are visualized in Fig. 1 for $N_T=N_R=4$, and will be further confirmed in the following analysis with practical considerations. Note that the wideband slope of STBC is hurt by its coding rate ($r=3/4$).

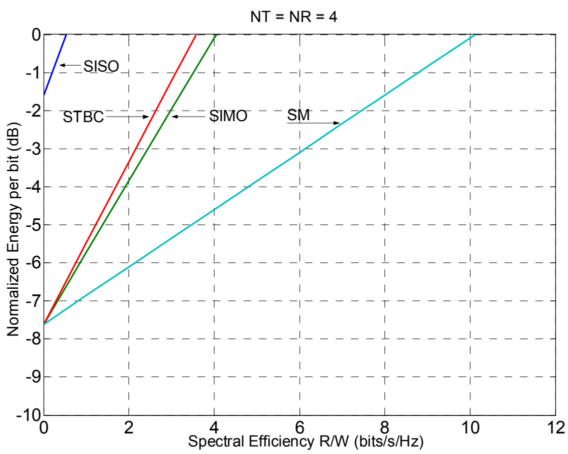

Fig. 1 Wideband behaviors with Rayleigh fading

IV. Energy Analysis of More Realistic Systems

In this section, these transmission strategies are examined with more realistic settings. Specifically, we relate the required $\bar{E}_b/N_0$ to the target BER and the size of the employed modulation constellation and antenna arrays, with the latter two essentially determining the system's spectral efficiency and data throughput (when the system bandwidth is fixed).

Throughput this paper, we assume recangle QAM modulation (with two independent equal-distance M_1- and M_2-PAM subchannels) with Gray mapping in our analysis for simplicity, which can be readily extended to other modulation schemes such as PSK. Except for the adaptive spatial multiplexing and antenna selection scheme in subsection D, equal-power and equal-rate communications are assumed.

A. Orthogonal Space-Time Block Coding

The average BER of an orthogonal STBC, following the performance analysis for diversity techniques in fading channels [8][9], can be very accurately approximated as

$$\bar{P}_{b,STBC} \doteq \frac{4}{\log_2 M}\left(1-\frac{1}{2M_1}-\frac{1}{2M_2}\right) \left(\frac{1-\mu}{2}\right)^{N_T N_R} \sum_{l=0}^{N_T N_R-1} \binom{N_T N_R-1+l}{l} \left(\frac{1+\mu}{2}\right)^{l}, \quad (11)$$

with

$$\mu=\sqrt{\frac{\alpha}{1+\alpha}} \text{ and } \alpha=\frac{1}{N_T}\frac{3\log_2 M}{\left[(M_1^2-1)+(M_2^2-1)\right]}\cdot\frac{\bar{E}_b}{N_0}, \quad (12)$$

which, for BER of interest, can be further simplfied as

$$\bar{P}_{b,STBC} \approx \frac{4}{\log_2 M}\left(1-\frac{1}{2M_1}-\frac{1}{2M_2}\right)\left(\frac{1}{4(\alpha+1)}\right)^{N_T N_R}\binom{2N_T N_R-1}{N_T N_R}. \quad (13)$$

The required $\bar{E}_b/N_0$ with target BER $\bar{P}_b$ for STBC can in turn be obtained as

$$\frac{\bar{E}_b}{N_0}\Big|_{STBC} \approx N_T \frac{\left[(M_1^2-1)+(M_2^2-1)\right]}{3\log_2 M} \left(\frac{1}{4}\left(\frac{4\left(1-\frac{1}{2M_1}-\frac{1}{2M_2}\right)\binom{2N_T N_R-1}{N_T N_R}}{\bar{P}_b \log_2 M}\right)^{1/N_T N_R}-1\right). \quad (14)$$

Note that by taking $N_T=1$ in (11)~(14), we readily get the analytical results for a SIMO system with maximum ratio combining, and further letting $N_R=1$ gives us results for SISO. We see that compared with a SIMO, STBC induces both the coding loss and the diversity gain (as each symbol is transmitted N_T times from different antennas), the latter of which typically dominates at high SNR. However, with the circuit energy consumption and the cooperation penalty taken into consideration, we will show that STBC actually assume little energy efficiency advantage over SIMO for SENMA.

B. Spatial Multiplexing with maximum likelihood Detection

The performance of spatial multiplexing with maximum likelihood detection can be tightly upper-bounded by a (weighted) sum of pairwise error probability (PEP). The summation can be over all pairwise error events (union bound) or over just a few dominant events (typically with minimum distance). An exact formula for the average PEP has been obtained in [4]

$$\overline{P(\mathbf{x}_j \to \mathbf{x}_i)}=\left(\frac{1}{1+r}\right)^{2N_R-1}\sum_{l=0}^{N_R-1}\binom{2N_R-1}{l}(r)^l, \quad (15)$$

with

$$r=\sqrt{\left(\tfrac{1}{2}\Gamma\right)^2+\Gamma}+\tfrac{1}{2}\Gamma+1 \text{ and } \Gamma=\|\mathbf{x}_i-\mathbf{x}_j\|^2/N_0. \quad (16)$$

Seemingly different, Eq. (15) is actually the same as the PEP in SIMO (the second line of Eq. (11) with $N_T=1$) with

$$\mu=\frac{r-1}{r+1} \text{ and } \alpha=\tfrac{1}{4}\Gamma, \quad (17)$$

or equivalently with $\|\mathbf{x}_i-\mathbf{x}_j\|^2=\|\Delta\mathbf{x}\|^2=d_{\min}^2$, where

$$d_{\min}^2=\frac{12\log_2 M}{\left[(M_1^2-1)+(M_2^2-1)\right]}\cdot\bar{E}_b \quad (18)$$

is the minimum distance of a rectangle M-QAM symbol with average energy per bit $\bar{E}_b$. Since the error performance is typically dominated by the minimum-distance error events, we expect that the performance of SM with ML detection closely approaches that of SIMO. Numerical results verify that the performance of equal-power and equal-rate SM with ML detection is within 1 dB of the single user SIMO upper bound. Therefore, in our study, it is sufficient to assume

$$\frac{\bar{E}_b}{N_0}|_{SM-ML} \approx \frac{\bar{E}_b}{N_0}|_{SIMO} . \quad (19)$$

Note that for given a target BER, SM with ML detection requires almost the same energy as SIMO, but the resulted spectral efficiency increases linearly with the number of transmit antennas. Alternatively, given a throughput and BER target, SM with ML detection has much better energy efficiency.

C. Spatial Multiplexing with Decorrelating Decision-Feedback Multiuser Detection

Direct implementation of maximum likelihood detection for SM systems involves prohibitive computational complexity. When $N_R \geq N_T$, Sphere decoding can be adopted to obtain the exact ML solution with polynomial complexity as long as the data rate is sufficiently below Shannon capacity limit [5]. Another widely employed sub-optimal detection method is the decorrelating decision-feedback multiuser detection (DDF MUD), which provides a fast approximate solution to the ML detection problem [12].

The joint error probability (JEP), i.e., the probability that at least one detected symbol is in error, of SM with DDF MUD is given by

$$\bar{P}_{JEP,SM-DDF} = 1 - \prod_{k=1}^{N_T} (1 - \bar{P}_{s,SM-DDF-PF}^{(k)}) , \quad (20)$$

where $\bar{P}_{s,SM-DDF-PF}^{(k)}$ is the average symbol error rate (SER) of the kth detected substream with perfect feedback, which coincides with that of a SIMO system with $(N_R - N_T + k)$ degrees of freedom. It is observed that at BER of interest

$$\bar{P}_{JEP,SM-DDF} \doteq \sum_{k=1}^{N_T} \bar{P}_{s,SM-DDF-PF}^{(k)} \doteq \bar{P}_{s,SM-DDF-PF}^{(1)} = \bar{P}_{s,SM-DDF}^{(1)}, \quad (21)$$

that is, the JEP is asymptotically dominated by the SER of the first detected substream, which experiences the least receive diversity. While Eq. (21) is a good upper bound for the true average SER, the performance gap is typically of several dBs and increases with the constellation size and number of antennas. When more accurate evaluation is required, we need to resort to the accurate SER expression [7]:

$$\begin{aligned} \bar{P}_{s,SM-DDF}^{(k)} &= \frac{1}{M^{k-1}} \sum_{\mathbf{x}_{k-1}} \\ &\left(\sum_{\hat{\mathbf{x}}_{k-1}} E\left[P(x_k \neq \hat{x}_k \mid \mathbf{x}_{k-1}, \hat{\mathbf{x}}_{k-1}, \mathbf{H}) \right] \prod_{m=1}^{k-1} E\left[P(\hat{x}_m \mid \mathbf{x}_{k-1}, \hat{\mathbf{x}}_{m-1}, \mathbf{H}) \right] \right), \end{aligned} \quad (22)$$

where $\mathbf{x}_i = [x_1, \cdots, x_i]^T$ is the vector of transmitted symbols up to the substream i and $\hat{\mathbf{x}}_i$ is the corresponding detected symbols. Instead of resorting to numerical evaluations, we make the following assumption to simply the calculation of Eq. (22), which is sensible in the low BER regime: *in each stage of detection, the detector either makes correct decision, or errors to the nearest neighbor*. With this assumption, the second line of Eq. (22) turns out to be invariant to the transmitted vector, and can be simplified as

$$\bar{P}_{s,SM-DDF}^{(k)} \doteq \sum_{\hat{\mathbf{b}}_{k-1}} E\left[P(x_k \neq \hat{x}_k \mid \hat{\mathbf{b}}_{k-1}, \mathbf{H}) \right] \prod_{m=1}^{k-1} E\left[P(\hat{b}_m \mid \hat{\mathbf{b}}_{m-1}, \mathbf{H}) \right], \quad (23)$$

where $\hat{\mathbf{b}}_{k-1}$ is a k-1 binary vector with 0 denoting correct detection and 1 erroneous detection for each corresponding substream. The components of Eq. (23) can be calculated as follows.

$$E\left[P(x_k \neq \hat{x}_k \mid \hat{\mathbf{b}}_{k-1}, \mathbf{H}) \right] = \bar{P}_{s,SIMO}\left(M, N_R - N_T + k, \kappa(k) \frac{\bar{E}_b}{N_0} \right) \quad (24)$$

with (c.f. (18))

$$\kappa(k) = \left(1 + \sum_{\substack{i=1 \\ \hat{b}_i = 1}}^{k-1} \frac{d_{\min}^2}{N_0} \right)^{-1} = \left(1 + \frac{12 \log_2 M}{\left[(M_1^2 - 1) + (M_2^2 - 1) \right]} \left\| \hat{\mathbf{b}}_{k-1} \right\|_1 \frac{\bar{E}_b}{N_0} \right)^{-1}, \quad (25)$$

where $\left\| \hat{\mathbf{b}}_{k-1} \right\|_1 = \sum_{i=1}^{k-1} \hat{b}_i$; and $\bar{P}_{s,SIMO}\left(M, L, \frac{\bar{E}_b}{N_0} \right)$ is the average SER of a SIMO system at SNR $\bar{E}_b / N_0$, employing rectangle M-QAM and L receive antennas (see IV A). Similarly,

$$\begin{aligned} E\left[P(\hat{b}_m \mid \hat{\mathbf{b}}_{m-1}, \mathbf{H}) \right] &= \hat{b}_m \bar{P}_{s,SIMO}\left(M, N_R - N_T + m, \kappa(m) \frac{\bar{E}_b}{N_0} \right) \\ &+ (1 - \hat{b}_m) \left(1 - \bar{P}_{s,SIMO}\left(M, N_R - N_T + m, \kappa(m) \frac{\bar{E}_b}{N_0} \right) \right). \end{aligned} \quad (26)$$

Eq. (23) can be numerically inverted to obtain the required $\bar{E}_b / N_0$ with target BER.

A closer look of Eq. (23) reveals that the diversity order of the average BER of SM with DDF MUD is $(N_R - N_T + 1)$, as opposed to N_R for SM with ML detection. Therefore SM with DDF MUD, though benefiting from simplicity in implementation, incurs significant performance degradation when N_T is close to N_R. The analysis of DDF MUD with optimal ordering (ODDF MUD) employed in the V-BLAST systems seems intractable, as it relies on the real channel realization [3]. But simulation results indicate that optimal ordering leads to no extra diversity gain.

D. Adaptive Spatial Multiplexing and Antenna Selection

Due to the randomness of the wireless fading channel, link adaptation techniques such as rate adaptation and power control are often exploited to improve the system performance and guarantee certain quality of service. On the other hand, one of the drawbacks with an MIMO system is the increased complexity and hardware cost due to the expensive RF chains required by each active antenna. It is of increased research interest recently to find a good antenna selection scheme that can significantly reduce such cost while incurring little performance loss. Antenna selection is especially meaningful for sensor network applications as it helps reduce the significant circuit energy consumption as well.

It is interesting to notice that link adaptation and antenna selection problems are actually coupled for MIMO systems, when suboptimal detection techniques such as DDF MUD are employed. This is because the decoupled subchannel gains (based on which link adaptation is executed) are determined by the active antenna subset, while some weak subchannels are naturally dropped during the link adaptation process. Motivated by this fact, we propose a joint antenna subset selection and link adaptation study for MIMO systems in [15]. Basically, given any number of active antennas, our algorithms are able to find a close-to-optimal solution for the selections of an antenna subset and corresponding bit and power allocation, in some simple recursive ways that are feasible for practical implementation.

In sensor applications, the adaptation process is conducted at the MA and the chosen nodes are informed of their operating modes via reverse signaling channels. Similar to the DDF MUD with optimal ordering, the analysis of adaptive spatial multiplexing and antenna selection seems intractable and we will turn to numerical simulations for its performance study.

V. SPECIFIC CONSIDERATIONS FOR SENSOR NETWORKS

The transmit energy consumption per bit of a communication link is given by [8][2]

$$E_{TX} = \frac{\xi}{\eta}\left(\frac{\overline{E}_b}{N_0}\cdot N_r\right)\cdot\frac{(4\pi)^2 d^\alpha}{G_t G_r \lambda^2}\cdot M_g, \tag{27}$$

where $\overline{E}_b/N_0$ has been examined in the previous section, N_r is the single-sided power spectral density of the receiver noise, $(4\pi)^2 d^\alpha / G_t G_r \lambda^2$ reflects the end-to-end loss in transmission, M_g is the link budget margin, and ξ/η is a coefficient accounting for the RF power amplifier effect with ξ the peak-to-average ratio of the modulation scheme and η the drain efficiency of the amplifier.

As we have mentioned, the energy analysis of the sensor networks should include two more important factors, the circuit energy consumption E_C and the cooperation penalty E_{CP}, as discussed below on a per-bit basis.

A. Circuit Energy Consumption

Due to the stringent energy constraints and (relatively) short transmission distances in sensor networks, the circuit energy consumption, largely neglected in previous study, should be explicitly addressed. As the SENMA architecture is assumed, we focus on the circuit energy consumption at the cooperative transmit nodes.

According to [2], the circuit energy consumption in transmission P_{CT} typically includes that of the digital-to-analog converter, the mixer, the transmit filters, and the frequency synthesizer, while in reception P_{CR} typically includes that of the analog-to-digital converter, the mixer, the receive filters, the frequency synthesizer, the low noise amplifier, and the intermediate frequency amplifier. We assume that these two values are the same for each sensor node. Therefore, the total circuit energy consumption per bit for a cooperative MIMO scheme in SENMA is given by

$$E_C = N_T \frac{P_{CT}}{R_b}, \tag{28}$$

where R_b is the data rate, given as $B\log_2 M$ for SIMO, $rB\log_2 M$ for STBC, $N_T B\log_2 M$ for SM, and $B\sum\log_2 M_i$ for adaptive SM, where B is the system bandwidth.

B. Cooperation Penalty

As the elements of the formed virtual antenna array are not wired together, cooperative nodes must communicate among themselves in advance to share information and coordinate for MIMO transmission. We assume that K_T out of N_T nodes have data to transmit. Each of the K_T data nodes broadcasts its information to all the other nodes in this group using different time slots. The energy consumption per bit required for such cooperation is given as

$$E_{CP} = K_T\left(\frac{P_{CT}}{R_b} + E_{TX,SISO} + (N_T - 1)\frac{P_{CR}}{R_b}\right), \tag{29}$$

where $E_{TX,SISO}$ is the required transmit energy per bit for the local SISO communications among cooperative sensor nodes. If the cooperative group has a small radius, the local transmission channels can be assumed to be AWGN, and the required $\overline{E}_b/N_0$ is given by

$$\frac{\overline{E}_b}{N_0}\Big|_{SISO,G} \approx \frac{\left[(M_1^2-1)+(M_2^2-1)\right]}{6\log_2 M}\left[Q^{-1}\left(\frac{\overline{P}_b\log_2 M}{4\left(1-\frac{1}{2M_1}-\frac{1}{2M_2}\right)}\right)\right]^2, \tag{30}$$

where $Q(\cdot)$ is the Gaussian tail function. If a Rayleigh fading modeling is still required for local transmission, the required $\overline{E}_b/N_0$ is given in IV A.

VI. NUMERICAL RESULTS

First, we make a comparison of the $\overline{E}_b/N_0$ – spectral efficiency tradeoff of several relevant transmission strategies in Fig. 2, a real-system counterpart of Fig. 1. Clearly in fading channels, receive diversity at the MA improves the energy efficiency by orders of magnitude. STBC adds in transmit diversity, further lowers the energy consumption. However, orthogonal designs with $N_T > 2$ don't seem to be effective as full rates can no longer be achieved (at most 3/4 for $N_T = 3,4$). On the other hand, SM with ML detection is much more energy efficient especially for high-throughput communications. Given N_T, the required SNR increases at a much slower slop as opposed to STBC, and increasing N_T boosts the throughput at little extra energy cost.

In reality, the SM scheme may be hindered by suboptimal detection due to complexity concerns. Fig. 3 reveals that, SM with DDF MUD (even with optimal ordering), while obtaining satisfactory performance for an over-determined system, results in significant degradation when N_T approaches N_R. On the other hand, link adaptation techniques, when available, fill this tremendous gap for a full-loaded system, and even outperform the equal-power equal-rate SM with ML detection. Note that adaptive SM also offers uniformly better performance over the best STBC scheme at all spectral efficiencies supported by QAM modulation.

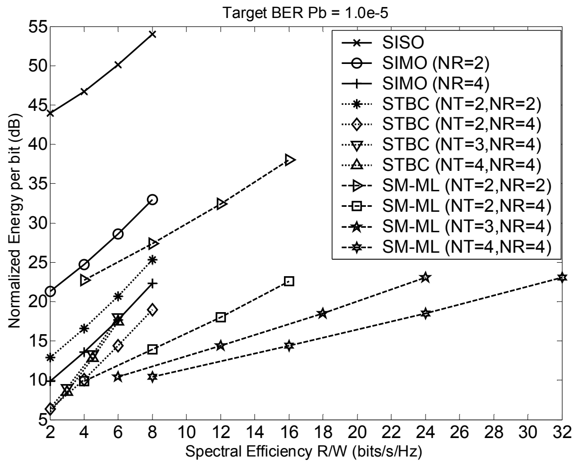

Fig. 2 Realistic systems with Rayleigh fading

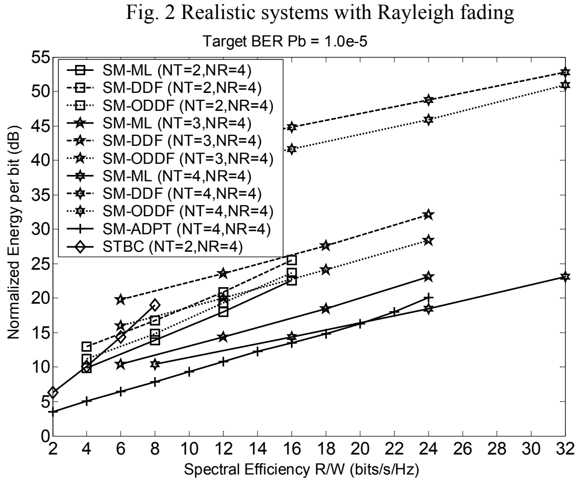

Fig. 3 Comparison of spatial multiplexing schemes in Rayleigh fading

Next, we investigate the energy efficiency of these MIMO transmission strategies in wireless sensor networks, taking into consideration the circuit energy consumption and the cooperation penalty discussed in Section V. The typical energy consumption values of various circuit blocks are quoted from [2], with $P_{CT} = 97.8$ mw and $P_{CR} = 112.8$ mw. A narrowband system at 2.5 GHz is assumed with $B = 10$ kHz. The path loss exponent is assumed to be 4 for local transmission among cooperative nodes and 2 for the transmission between the cooperative sensor group and the mobile agent. The following values are taken for the other parameters in Eq. (27): $\eta = 0.35$, $N_r = -161$ dBm/Hz, $G_t G_r = 5$ dBi, and $M_g = 40$ dB. For local cooperation in sensor fields, we assume a cluster radius of 1m, and $K_T = 1$ data node, which optimizes its constellation size during local broadcasting to minimize the cooperation penalty E_{CP}. An AWGN channel is assumed for local transmission as opposed to the Rayleigh fading channel for the sensor-to-MA transmission.

Aside from the possible cooperation penalty, the total energy consumption of a transmission scheme includes two parts: E_{TX} and E_C. When the transmission distance is short, E_C dominates and one would like to employ a large constellation size and increase the throughput to reduce E_C; with the increase of the transmission distance, E_{TX} gradually takes over and one would like to reduce the constellation size to decrease the required $\bar{E}_b / N_0$. We know that STBC endeavors to decrease the BER rather than to increase the data rate (as opposed to SM). So we compare the total energy expenditure of SIMO and STBC with optimized modulation (with respect to the transmission distance) in Fig. 4, where the slope changes of each curve indicate the changes of the employed constellation. It is found that, even though STBC assumes some advantage in transmit energy efficiency as shown in Fig. 2, such advantage fails to justify the additional circuit energy consumption and cooperation penalty unless for a very large transmission distance (500 m in this example), which may be unacceptable for the SENMA architecture.

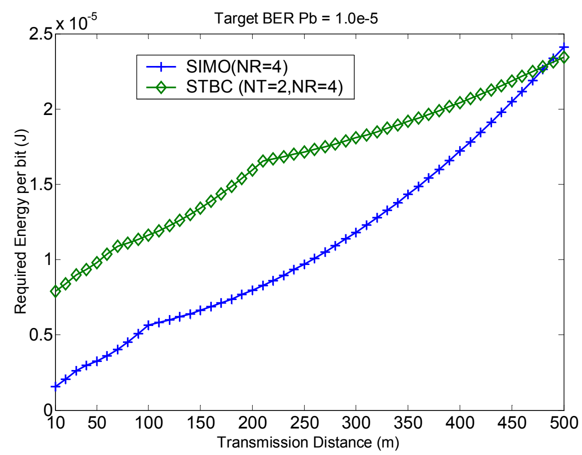

Fig. 4 Total energy expenditure of SIMO and STBC in SENMA without throughput constraints

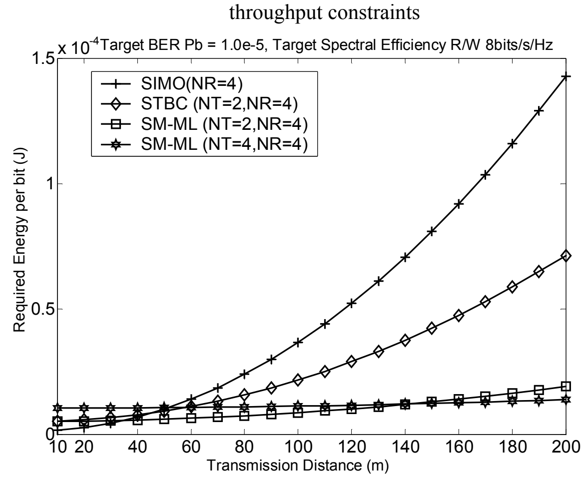

Fig. 5 Total energy expenditure of SIMO, STBC and SM-ML in SENMA with throughput constraints

On the other hand, we learn from Fig. 2 that SM with ML detection offers substantial energy savings for high-rate communications, which significantly reduces the critical distance over which MIMO transmission overtakes the corresponding SIMO. As shown in Fig. 5, a 2×4 spatial multiplexing system with ML detection outperforms the corresponding SIMO when $d > 35$ m and is uniformly better than the Alamouti STBC scheme when the target spectral efficiency is 8 bits/s/Hz. A 4×4 SM-ML is no better than a 2×4 one until $d > 140$ m, mainly due to the extra circuit energy consumption. Therefore, depending on the specific applications, it is not always better to have a larger group of nodes cooperative in transmission for better energy efficiency.

We know from Fig. 3 that adaptive SM outperforms equal-power equal-rate SM with ML detection in transmit energy efficiency. When the circuit energy consumption is also significant, the advantage of adaptive SM is expected to be larger, due to less antenna usage and circuit energy consumption. We can even deliberately set an upper limit on the total number of simultaneous-on transmit antennas (cooperative nodes) for this purpose.

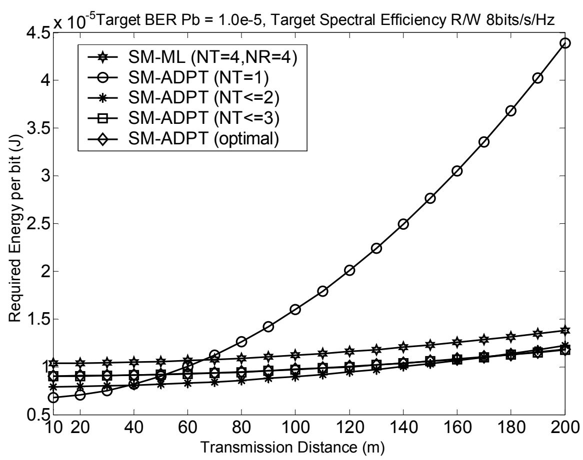

Fig. 6 Total energy expenditure of SM-ML and SM-ADPT in SENMA

Fig. 6 compares the total energy expenditure of equal-power equal-rate SM with ML detection and several adaptive SM schemes with $N_T = N_R = 4$. The adaptive SM is realized through our joint antenna selection and link adaptation techniques in [15], where we can restrict the number of active antennas. Removing such restrictions (i.e., allowing $N_T \le 4$) leads to the optimal one (c.f. Fig. 3). We see from Fig. 6 that the optimal adaptive SM offers uniform performance improvement over the equal-power equal-rate SM-ML. However, it is also shown that up to $d = 40$ m simply selecting one best node yields the best performance, and for $40\text{ m} < d < 170\text{ m}$ selecting the best two nodes suffices. Selecting up to three out of the four available nodes incurs almost no performance loss compared to the optimal one. Clearly setting an upper limit on the total active transmit antennas simplifies the antenna selection and link adaptation process. Therefore, the stringent energy consumption in wireless sensor networks adds a new element in the study of link adaptation for MIMO systems.

VII. Conclusions

In this paper, the energy efficiency of several important MIMO transmission techniques is studied in the context of a hierarchical wireless sensor network. We have shown that, even though space-time block codes assume some advantage in transmit energy efficiency over the corresponding SIMO approach, such advantage fails to justify the additional circuit energy consumption and cooperation penalty unless for a very large transmission distance. On the other hand, spatial multiplexing offers substantial energy savings for high-rate communications, which significantly reduces the critical distance over which MIMO transmission overtakes the corresponding SIMO in sensor networks. Finally, it is found that the link adaptation technique, when applicable, is especially meaningful for sensor network applications as it helps reduce both the transmit energy and the circuit energy consumption simultaneously.

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